Final Scientific/Technical Report

Continuation of the Application of Parallel PIC Simulations to Laser and Electron Transport Through Plasmas Under Conditions Relevant to ICF and SBSS

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Executive summary:

One of the important research questions in high energy density science (HEDS) is how intense laser and electron beams penetrate into and interact with matter. At high beam intensities the self-fields of the laser and particle beams can fully ionize matter so that beam -matter interactions become beam-plasma interactions. These interactions involve a disparity of length and time scales, and they involve interactions between particles, between particles and waves, and between waves and waves. In a plasma what happens in one region can significantly impact another because the particles are free to move and many types of waves can be excited. Therefore, simulating these interactions requires tools that include wave particle interactions and that include wave nonlinearities. One methodology for studying such interactions is particle-in-cell (PIC) simulations. While PIC codes include most of the relevant physics they are also the most computer intensive. However, with the development of sophisticated software and the use of massively parallel computers, PIC codes can now be used to accurately study a wide range of problems in HEDS. The research in this project involved <u>building</u>, <u>maintaining</u>, and <u>using</u> the UCLA parallel computing infrastructure. This infrastructure includes the codes OSIRIS and UPIC which have been improved or developed during this grant period. Specifically, we used this PIC infrastructure to study laser-plasma interactions relevant to future NIF experiments and high-intensity laser and beam plasma interactions relevant to fast ignition fusion. The research has led to fundamental knowledge in how to write parallel PIC codes and use parallel PIC simulations, as well as increased the fundamental knowledge of HEDS. This fundamental knowledge will not only impact Inertial Confinement Fusion but other fields such as plasma-based acceleration and astrophysics.

Comparison of accomplishments with goals and objectives:

The goals and objectives were:

I. the development and maintenance of an infrastructure for parallel PIC computing.
II. the application of parallel PIC simulations to traditional areas of laser plasma interactions relevant to NIF.
III. the application of parallel PIC simulations to emerging areas of high intensity laser and electron beam transport relevant to the fast ignitor.
IV. the training of graduate students in high-energy density science and high-performance computing (we will support 3 students).

We successfully met these objectives. We did develop and maintain a parallel PIC infrastructure that is now recognized as state-of-the-art and is used throughout the world. As seen below we have made progress in understanding laser plasma instabilities of relevance to NIF (two plasmon decay and Stimulated Raman Scattering) and in understanding high intensity laser and beam plasma interactions. We have also trained post-doctoral researchers and students. One post-doctoral researcher is now a professor at the University of Rochester and three students will be graduating in the next 1 to 2 years.

Summary of project activities:

Parallel code Infrastructure (work done by V.K. Decyk and F.S. Tsung):

OSIRIS: OSIRIS is a fully explicit, multi-dimensional, fully relativistic, fully parallelized, fully object-oriented PIC code. Parallelization is done using domain decomposition with MPI. There are 1D, 2D, and 3D versions that can be selected at compile time by changing one line of code. It has been ported to a variety of parallel computing platforms and been run for ~5,000,000 node hours without a major issue. It has load balancing, open boundary conditions, and a collision model. One of OSIRIS' strongest attributes is a sophisticated array of diagnostic and visualization libraries.

UPIC: The UCLA Parallel PIC Framework (UPIC) is a unified environment for the rapid construction of new parallel PIC codes. It provides trusted components from UCLA's long history of PIC development, in an easily accessible form, as well as a number of sample main codes to illustrate how to build various kinds of codes. UPIC contains support for electrostatic, Darwin, and fully electromagnetic field solvers, as well as relativistic particles. The field solvers are spectral (FFT) based. For the 2D version open (Vacuum) boundary conditions for the electrostatic solver (using Hockney's scheme) and dynamic load balancing for particles have been implemented. It also contains conducting (Dirichlet) boundary conditions as well as mixed periodic/conducting boundary conditions. Much of UPIC was written during the past grant period.

OSIRIS.analysis: Visualization and data analysis is an essential and totally nontrivial part of any parallel numerical laboratory. We developed a very sophisticated set of data analysis and visualization routines based on IDL and open DX, called OSIRIS.analysis. We have made many improvements on the post-processing of OSIRIS data, expanding both OSIRIS' ability to dump data, and the capability of our IDL scripts to post-process and analyze these output. We have added new particle tracking that allows individual orbits to be tracked across processor boundaries, and keep detailed time history of energy gain. This is an important tool for understanding of acceleration mechanisms and particle transport.

In the past, we have been able to quickly convert a series of snapshots into a movie so the time evolution of a particular quantity can be presented in a very intuitive manner. We now have the ability to Fourier transform time series data in an arbitrary way. A series of snapshots can be presented in (x,t), (x,••), (k_x,t) and (k_x,•) space. This ability allows us to measure growth rate as a function of wavenumber, and study the excitation of plasma waves in (k_x,••) space. This can be done either for the entire simulation or with a sliding window to study short-lived events. We have added wavelet based post-processing tools, both as a filter and as a mathematically rigorous way to separate the various length scales in the simulation data. We have also added correlation functions in IDL used to generate the bi-coherence plots presented later in the $2\omega_p$ section.

Conventional Areas of Research for ICF

Nonlinear Optics of Plasmas at Intensities Relevant to NIF (work done by Dr. F.S.Tsung and the graduate students, B. Winjum and J. Fahlen)

Intrinsic merit: The nonlinear optics of plasmas is the discipline of determining how electromagnetic waves are scattered and absorbed by free electrons and ions. In order that the laser energy reaches the critical surface or the hohlraum wall, it must propagate through long (~ $1000\lambda_o$) regions of underdense plasma. In the underdense corona the lasers can be susceptible to numerous parametric instabilities. In these instabilities, the incident laser decays or scatters off electron and/or ion fluctuations into other electromagnetic waves. These processes also cover a large range of space and time scales. As a result, understanding coronal physics is a grand theoretical and computational grand challenge.

As part of this challenge, we propose to emphasize the following topics for intensities between $I\lambda^2 = 10^{14}$-10^{16} W/cm^2 /μm^2. The goal is to strike a balance between simulations which study the basic science and which model specific plasma and laser parameters of direct relevance to ICF.

The coupled $2\omega_p$/ Stimulated Raman Scattering Instability

Intrinsic merit: The two-plasmon decay ($2\omega_p$) instability is the decay of an electromagnetic wave into two electrostatic waves (plasmons). It can only occur near the quarter critical density layer and for P-polarized light. Wavebreaking of the plasmons from $2\omega_p$ can generate > 100keV electrons which can cause preheat and it prevents laser energy from reaching the critical surface of the hohlraum. Therefore, it is of concern for ICF and SS.

This is arguably the most complex laser-plasma instability. Its linear growth is complex because it is inherently multi-dimensional, one of the daughter waves is neither longitudinal nor transverse, and the daughter waves are highly dispersive so they are sensitive to density gradients and finite spot size effects. The nonlinear state is very complex because wave particle interactions are ubiquitous, a broad spectrum of daughter waves are excited which beat causing stochastic electron acceleration and generating large amplitude ion modes which in turn cause profile steepening.

Progress on $2\omega_p$ instabilities: In collaboration with Dr. Afeyan, we have investigated the physics of $2\omega_p$ for a single hotspot, in plasma conditions relevant to NIF. Using OSIRIS, we obtained results in good agreement with the linear theory developed by Afeyan and Williams (see fig. 1). This theory parametrized the $2\omega_p$ problem into three parameters, $\tilde{v} \equiv \varepsilon \omega_{pe} v_{osc}/2c$, which is proportional to the absolute growth rate, ε_{nL}, which describes the length scale of the density, and $\tilde{\beta} \equiv \sqrt{\varepsilon} v_e^2 / \tilde{v}_{osc}$, which describes the lateral convection of the plasmons. The most unstable perpendicular mode occurs at $\tilde{\beta} k_{\perp} = 2/3$. The instability threshold in a linear density gradient in these normalized units is $C_{MULT} \equiv \left[\tilde{v}_{osc} / (\tilde{\beta} \varepsilon_{nL})\right] / \left[1/2(3/2)^{3/2}\right] > 1$. We performed PIC simulations to verify the linear theory in a variety of plasma conditions. For large values of $\tilde{\beta}$ and finite spot sizes, the instability can be suppressed by lateral localization. We have also verified this effect in our PIC simulations. In addition, we have performed simulations over a large range of C_{MULT} to check the range which linear theory can be applied. These simulations differ significantly from those done nearly two decades ago in that here $\tilde{\beta}$ is much larger, 8.7 vs. .15. Our simulations are challenging because the system size and the number of particles per cell need to be quite large.

In the simulations where the ions are immobile, the saturation mechanism is due to wave-breaking. The maximum longitudinal electric field in our simulations reaches level which is within 20% of the amplitude predicted by Coffey . Consequently, near saturation, the plasmons become large enough to trap and pull bulk electrons out to velocities comparable and larger than the phase velocity of plasmons, forming a tail with a slope (temperature) comparable to the mv_{ϕ}^2 of the most unstable plasmons.

In the nonlinear stage of this instability, the dynamics of the background ions (which are treated as an immobile background in the linear theory) is important.

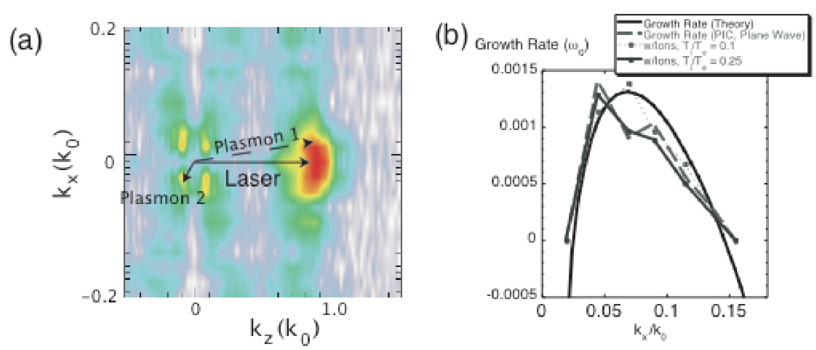

Figure 1: Comparison between linear theory (of Dr. B. B. Afeyan) and PIC simulations. The normalized simulation parameters are $\tilde{\beta}$=8.7, $\varepsilon_{nL} = 1.47x10^{-4}$, and $C_{MULT} = 2.4$.

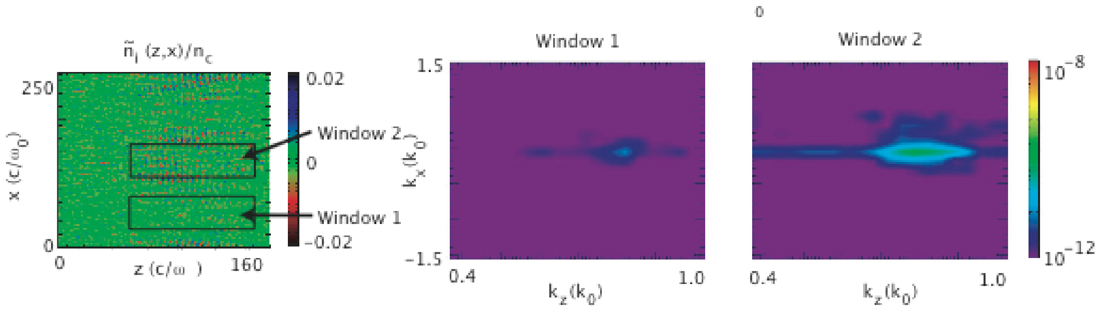

Figure 2: Bicoherence diagnostics for two small regions (windows 1 and 2) in the simulation. In window 2, there exists a large fluctuation and the bicoherence is also large. In Window 1, there is very little ion fluctuation and consequently the bicoherence is also small. This confirms that the ion fluctuation is caused by the beating of the most unstable plasmon with a counter-propagating plasmon.

The role of ion dynamics in the saturation of $2\omega_p$ was first suggested by Langdon et al., in their seminal paper. They argued that plasmons beat together creating an enhanced level of ion flucuations. In our low $\tilde{\beta}$ regime, the plasmons with the largest wavenumbers move axially. As a result they axially convect out of the interaction region before moving laterally. We find that the ion density fluctuations are due to the beating of two axially and counter-propagating plasmons. This axial beating requires one of the plasmons to be reflected from its turning point. This is confirmed using a bicoherence diagnostic. In 2D, the bicoherence,

$$b_\phi(\underline{k}_1,\underline{k}_2;t) = \phi_1(\underline{k}_1,t)\phi_2(\underline{k}_2,t)\phi_3^*(\underline{k}_1+\underline{k}_2,t) \,/\, \sqrt{\left|\phi_1(\underline{k}_1,t)\phi_2(\underline{k}_2,t)\right|^2 \left|\phi_3(\underline{k}_1+\underline{k}_2,t)\right|^2} \ ,$$

where ϕ_1 and ϕ_2 are longitudinal electric fields and ϕ_3 is the ion density, is a 4 dimensional quantity at any given time. However, by assuming that one plasmon, k_1, consists only of the most unstable plasmon, the bicoherence is now strictly a function of k_2, the reflected plasmons. Fig. (2) shows there is a strong correlation between the bicoherence signal and the ion fluctuation levels and the signal is largest for large $k_{||}$. We are currently writing two papers on simulations already performed.

Stimulated Raman Scattering of single speckles

<u>Intrinsic merit:</u> Stimulated Raman scattering (SRS) can reduce the amount of energy coupling to the hohlraum wall, it can negatively impact implosion symmetry, and it can produce hot electrons which preheat the target in both direct and indirect drive. Understanding the growth and saturation of SRS is necessary for the ultimate control of this instability and the successful operation of inertial confinement fusion.

For the laser and plasma parameters of ICF experiments, SRS involves highly nonlinear and kinetic effects. A thorough understanding of SRS is predicated upon an understanding of how plasmas saturate, multiple-scattering events, competition between forward and backward scattering, plasma inhomogenieties, rescattering of the backscattered and forward scattered light, and the local behavior of plasma/EM wave generation and dispersion. All of these may be simultaneously important and create a complex array of behavior.

A fundamental question is: how driven plasmons saturate and dissipate? Do they wavebreak? Do they evolve into stable nonlinear modes such as BGK or KEEN waves? Do they become unstable due to self-modulational instabilities such as the trapped particle instability? Do they saturate due to nonlinear frequency shift detuning? Or do discrete particle effects such as Cerenkov emission of plasmons relax the distribution function? And how are these processes modified due to multi-dimensional effects?

Full PIC, e.g., OSIRIS and UPIC, can address **all** of these questions.

<u>Recent progress on SRS:</u> During the past grant period, we have attempted to model the published experimental results of Montgomery et al., the simulation results of Vu et al., and NIF conditions, including high-temperature hohlraums. These results clearly demonstrate the utility and robustness of full PIC.

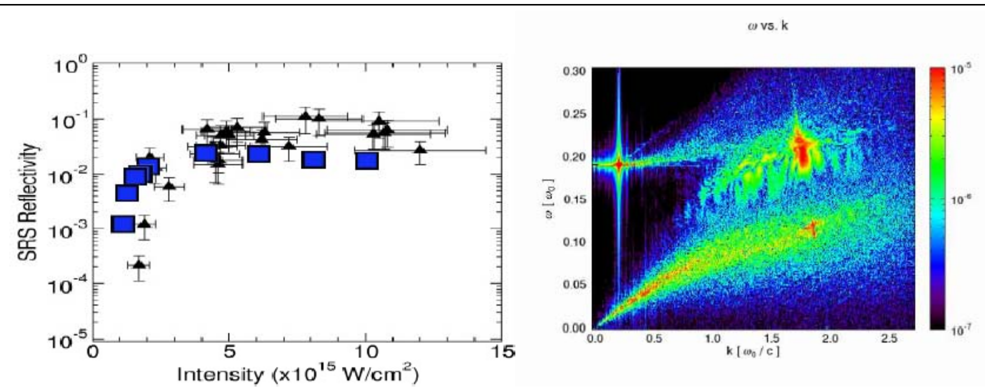

Figure 3:a) plasma reflectivity vs. laser intensity and b) ω vs. k spectra of plasma waves.

Montgomery et al. published experimental results of SRS reflectivity from a single laser hot spot as a function of driving laser intensity. Preliminary 1D OSIRIS simulations with similar parameters have produced similar reflectivities: a steep onset in reflectivity around 1-2 10^{15}W/cm^2 is seen, with average reflectivities of a few percent when the laser intensity is above 2 10^{15} W/cm^2. In these simulations we also observe the generation of flattened distribution functions, the generation of nonlinear structures with $\omega<<\omega_p$, and the multiple occurrence of SRS. This is illustrated in Figure 3 where the average reflectivity is plotted vs. intensity and a snapshot of the ω vs. k spectra of plasmons in units the incident laser's ω_0 and ω_0/c respectively is shown. Dominant modes are seen along the Bohm-Gross curve for both backscatter (~1.7) and forward scatter (~.2). In addition a broad spectrum is seen at low frequencies and wave numbers, corresponding to phase velocities that reside within the flattened part of the distribution function.

Originally, we primarily focused on a comparison with results published by Vu et al. which relied on a reduced PIC code. These results indicated that backward SRS saturated at higher than expected levels due to a reduction in the Landau damping rate from particle trapping. The trapping led to a nonlinear frequency shift which eventually detuned the backward SRS. We observed many similarities but also many differences. Figure 3 is a time vs. position plot of the longitudinal electric field for a 1D simulation.

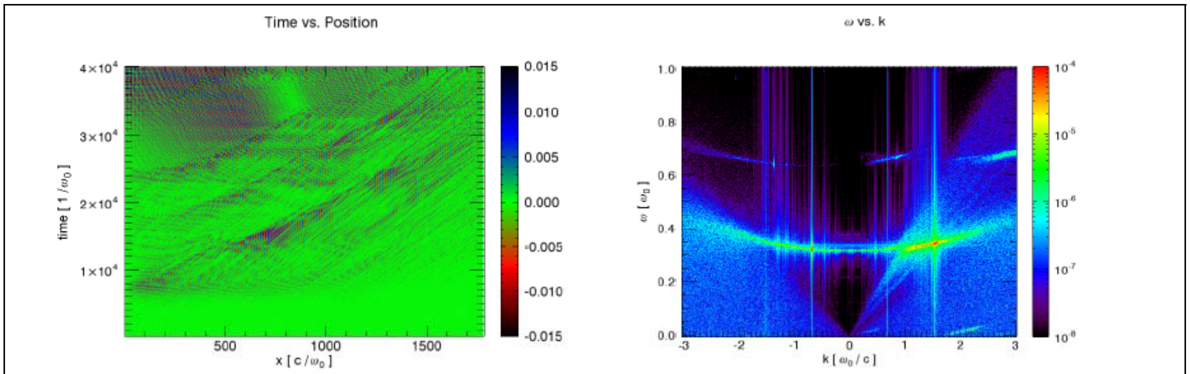

Figure 5: a) time vs. x plot of the plasmon E-field and b) plasmon ω vs. k plot.

The left image shows the bursty behavior of the plasma waves within the simulation window, as well as the specific position within the plasma where the waves grow, the velocities at which they travel, and the growth of rescatter (backward Raman scattering of the initial SRS). The right image is an ω vs. k plot of the same field at a given time. The units are in the incident laser's ω_0 and ω_0/c respectively. It reveals the basic Bohm-Gross dispersion curve, the initial SRS (backward and forward) at (1.5, 0.4), the rescatter at (-0.7, 0.35), and the generation of harmonics. Additional analysis of these plots reveals a rich tapestry of waves, harmonics, and beats.

To make connection with NIF, we have performed simulations where the electron temperature is slowly increased from 1.5 keV to 4 keV. Additionally, we have performed simulations with parameters expected in 300 eV and 350 eV radiation temperature hohlraums. Multiple scattering events and the competition of forward and backward SRS are expected to be at play under HEDS conditions as well. OSIRIS simulations have shown evidence of all of these effects.

As the laser travels through the hohlraum, the plasma will not be completely homogenous. Simulations with a slightly increasing density gradient have shown interesting behavior. Time vs. k plots of the longitudinal electric field, show SRS at k ~1.5 and rescattering which streaks in k-values from k ~0.5 to 0.7. The conclusion is that the plasma wave is generated at a specific density (a specific k) and shifts in k as it travels up the density gradient. Once the original wave has left, another can be generated at the same spot, and this process recurs. This same process occurs in homogenous plasmas and we believe this determines the recursion time in other simulations.

All of the afore-mentioned simulations have been 1D, but we have done numerous 2D simulations to study multi-dimensional effects. The 2D simulations included plane waves and Gaussian waves. 2D simulations for Gaussian pumps of both the Montgomery et al., experiment and NIF parameters show approximate one-dimensional behavior.

Nonlinear Optics of Plasmas at Relativistic Intensities (this work was done by Dr. C. Ren [now a professor at Rochester] and a graduate student, M. Tzoufras)
Intrinsic merit: The nonlinear optics of plasmas at relativistic intensities is the subject of how relativistically intense radiation propagate through matter. This discipline combines relativistic and ultra-fast physics. Two subjects driving this development are the fast ignitor concept and high-gradient plasma accelerators. The focused intensity can approach 10^{22} W/cm^2, at this intensity an individual electron wiggles with an energy exceeding 100 MeV, and the radiation pressure near a Tbar. In fact, at these intensities free electrons have much higher momentum in the forward direction than in the laser's E-field direction.

Recent progress: In collaboration with Imperial College and RAL, we have been modeling experiments carried out at the Vulcan Petawatt facility at the Rutherford Appleton Laboratory (RAL). In these experiments a 650fs, 1μm, 160 J laser is focused onto a gas jet. The resulting plasma density ranges from 10^{19} to 10^{20} cm^{-3} with an axial length of ~2mm. These experiments have observed 10 MeV ions expelled radially as well as 300 MeV electrons in the forward direction. Using OSIRIS, it was determined that the ions arise from an ion acoustic shock driven by the transverse ponderomotive force. The energetic electrons appear to arise from a combination of stochastic and betatron resonance effects. Using the particle tracking diagnostic, we have determined that the electron energy comes almost exclusively from the component of the electric field transverse to the laser propagation direction. When the PW class laser propagates through the underdense plasma it expels plasma electrons radially. The resulting space charge pulls the ions out creating the shocks. Residual electrons left in the channel experience both the fields of the laser and that of the ion column. Gahn et al., have shown that a betatron resonance is possible between the oscillations in the laser field and in the ion channel. However, it is not straightforward for electrons to come into resonance, particularly for very tenuous plasmas. We find that electrons are stochastically accelerated up to an energy at which they can get into a betatron resonance.

Petawatt laser plasma interactions:
Intrinsic merit: At these ultra-high intensities the radiation pressure becomes enormous. The radiation pressure is related to the laser intensity by the formula P_r = .3 Gbar I[10^{18} W/cm^2. Therefore for I = 10^{20} W/cm^2 the radiation pressure is 30 Gbar! When such a laser impinges upon an overdense solid target the laser begins to drill a hole. As this occurs electrons are shot forward with energies of 10's of MeV. These two effects are essential to the fast ignitor fusion concept where a high-intensity laser pulse needs to drill a hole to the dense core of a laser pellet and ignite it with a burst of ~2 MeV electrons. The pellet core is 1000 times solid density and the electron beam density approaches solid density, 10^{23} cm^{-3}, As a consequence the electron beam generates huge magnetic fields, i.e., > 1GigaGauss

This process is obviously highly nonlinear with much unexplored physics. There has been some recent positive results in this area in both 2D and 3D PIC simulations. We propose to use simulations to obtain distribution functions to be used for studying the next topic.

<u>Recent progress:</u> A significant effort has been made to study the interaction of high-intensity lasers with overdense plasmas. A series of very large simulations were carried out. The simulation parameters were carefully chosen based on a combination of physical, numerical, and dimensionless scaling considerations, as well as a balance between attempting to realistically model fast ignition parameters and to make comparison to previously published simulation and experimental results. The simulation box size was $100\lambda_0 \times 100\lambda_0$ (12032 cells × 12032 cells) where λ_0 is the laser wavelength. There were 4 electrons (7.5 keV) and 4 protons (1keV) per cell. The plasma had a diameter of $51\lambda_0$ with a dense core ($n=40n_c$ in a diameter of $32\lambda_0$) surrounded a coronal ring. In all cases, the target was isolated from the boundaries using a vacuum buffer region to reduce the influence of the boundary conditions. The laser had a peak intensity of $I=0.96\times10^{20}$ $(1\bullet m/\bullet_0)^2$W/cm^2 and with a diffraction limited spot size $w_0 = 7.5\lambda_0$. A typical simulation duration is 1ps for $\lambda_0 = 1\bullet m$.

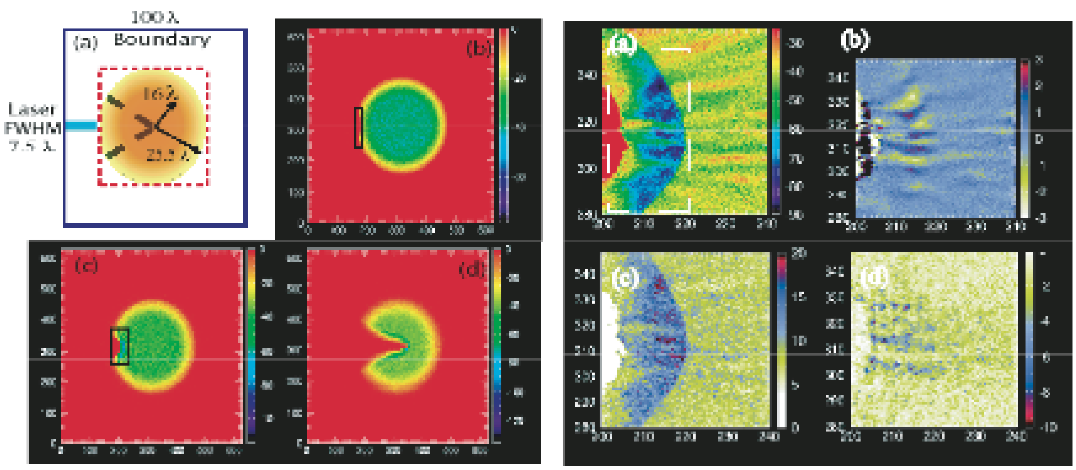

Figure 5: Left: (a) A sketch of the simulation geometry. (b-c) Electron density profile for a circular target with p-polarization at t=340 fs (b) and t=964 fs (c). (d) Electron density profile for a wedged target with p-polarization at t=964 fs. Right: Blow up of region in box in the left figure. For a circular target with p-polarization at t=964 fs, (a) electron density (in units of n_c), (b) magnetic field b_3 (in units of $mc\omega/e$), (c) return current (in units of $n_c ec$), and (d) fast electron current. Distance in units of $\lambda_0/2\pi$ and density in units of n_c.

The simulations indicate that the accepted view that the incoming flux of energetic electrons eventually coalesces into a single filament is incorrect. Previous studies used much small system sizes so they were dominated by the transverse boundary conditions. In our results the fast electrons do not merge into a single filament. We know that the origin of this difference lies in the different target dimensions and whether the target is isolated. With smaller simulation dimensions the results looks similar at early times; but once electrons, which flow outward from where the laser is incident on the plasma, hit the transverse boundary, the physics changes dramatically.

Another important difference between previous results and our new results is in the electron spectrum. We observe a power-law spectrum rather than a two-temperature Maxwellian. When we reduce the size of our simulation, we also observe a two-temperature Maxwellian. The electron spectrum is the most important input for any non-PIC code to correctly model the subsequent energy transportation in the cold dense core, so obtaining an accurate description of the distribution is essential.

In addition, based on the simulation results we have identified key research directions in basic HED science. We have reexamined the theory for the Weibel instability and have examined ion acoustic shocks for relativistic electron temperatures. We find that it is important to include a current neutralizing return current and the ions to maintain space charge neutralization. For the parameters in the simulations the incoming flux of electrons have too large of a transverse energy spread to filament on their own. However, including a return current as well as space charge neutralization from the ions leads to filamentation on the time scale of the ions in the shock region.

Ultra-Intense Electron Beam Transport

<u>Intrinsic interest:</u> The need to understand the unique aspects of the fast ignitor is sure to spawn the study of ultra-intense electron beam-matter interactions as an exciting new discipline. As it presently stands, the fast ignitor requires that a 5KJ beam of ~1MeV electrons propagate through ~ 50μm of a high density plasma within 5-10 ps. This corresponds to a GAmp of current carried by 10^{16} electrons or 1 mC. The cross section of this beam is envisaged to be 10 μm, so the beam has a power density of ~ 10^{21}W/cm^2 and a density of ~ 10^{23}cm^3. Compare this to the upper limit of 10^{15}W/cm^2 for electrons ablating the pellet. Viewed another way, the current density is 10^{15}A/cm^2 so that in the 10^{23} cm^{-3} plasma there is roughly an Alfvén current flowing within each c/ω_p. Therefore, if the beam begins to filament it could stop. Furthermore, the plasma's ability to generate a return current might be limited by the collisonality of the plasma. This is further complicated by the inhibition caused by the beam's own field. For example, a GA in 10 μm generates a ~B- field of 100 Giga-Gauss! So even if most of the current is neutralized large residual fields remain.

To address this physics, during this grant period we examined:

A Generalized "Weibel" Instability: Effects of non-Maxwellian distribution functions and space charge forces.

<u>Intrinsic interest:</u> Determining how an intense current (>> the Alfven current) penetrates into a weakly collisional plasma is

fundamental question in high-energy density science. In some cases the real issue is how a incident flux of electrons penetrates inward from a boundary. This heat flux induces a return current. The return current and the inward flowing particles can have grossly different transverse temperatures. Futhermore, the collisionality of the slower moving return current can be greater. This makes the problem very complicated. Fast ignition relies on the generation of a hot population of particles in one region which propagate through substantial regions of plasma to a dense core where they deposit their energy. It had been hoped that the inward flowing electrons would generate a self-channeling magnetic field. Our simulations and show otherwise. Most theories of this process either assume the heat flux is modeled as an inward flowing beam (a bump on tail) or that the electrons are modeled as bi-Maxwellian. It is also assumed that the unstable mode is purely transverse, i.e., space charge effects are not important. If a bump on tail is assumed and the beam and plasma have different temperatures then the beams will pinch at different rates and space charge effects will be important.

Recent progress: We have used PIC simulations to improve our understanding of these processes. From these simulations we get the exact form of the particle distribution function, which looks nothing like a "bump-on-tail" but is rather a monotonically decreasing -though highly non-Gaussian - function. We have also recognized that both the temporal as well as spatial development of the instability are different than that predicted from existing theory. We have begun to develop a theory for arbitrary distribution functions and for electrostatic coupling to the electromagnetic mode. This work comprised the Masters Thesis of M.Tzoufras.

Electromagnetic instability for arbitrary particle distribution functions: We begin with nonrelativistic distribution functions. We expand in terms of a complete set of Hermite-Gaussian modes. The details of the distribution function become important in the kinetic (weak anisotropy) limit of the instability. An interesting result of our formalism is that for a distribution function which is Gaussian in the direction of the unstable wavevector (z) and arbitrary in another direction (x), the instability criterion becomes: $\langle v_x^2\rangle > \langle v_z^2\rangle$ instead of $T_x > T_z$. It turns out that only the zeroth and the second order Hermite modes along x enter the dispersion relation. The result becomes more complicated when the distribution function is not separable. We have used this theory to study several classes of distribution functions. We have verified our results with 2D and 3D PIC simulations. We are currently preparing this work for publication.

Coupling of electrostatic modes to the current filamentation instability: When drifting electron beams with different transverse temperatures orthogonal to the drift go unstable to a transverse two-stream/Weibel like instability, they pinch at different rates in a self-generated magnetic field. This leads to a charge imbalance and space charge forces which lower the growth rate and cause the ion background to respond. Therefore, it is not true that colder beams lead to higher growth rates as a purely electromagnetic mode suggests. We have derived a growth and threshold for a distribution consisting of an arbitrary number of drifting Maxwellians. In Fig 7(a) we plot the growth standard growth rate against wave number as well as the growth rates including space charge and including ion motion for a case of two counter streaming Gaussian electrons and stationary ions. We have used the PIC code OSIRIS to verify this new theory. An example is shown in Fig. 6(b) where a 3D isosurface plot is shown for the density of the cold drifting species. In Fig. 7 we show 2D contour plots of the warm backward flowing electrons, the cold electrons, and the ions. The ions follow the colder electrons. Excellent agreement has been found between theory and simulations and we are preparing this for publication.

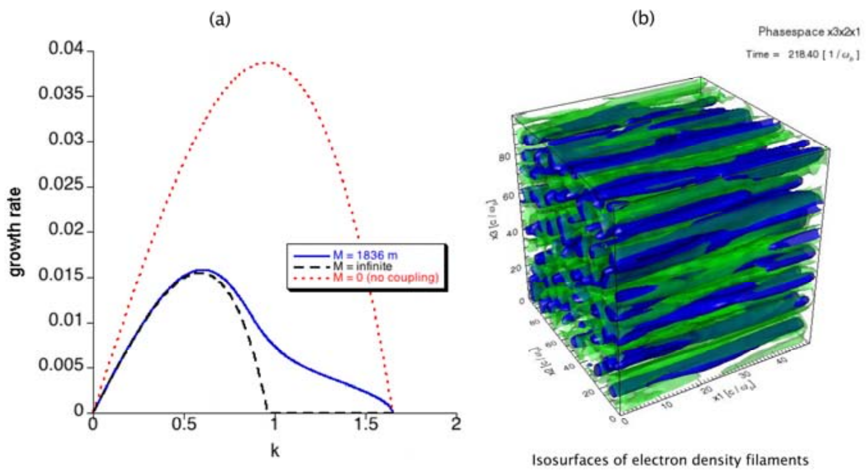

Figure 6: (a) Growth rate as a function of wave number. (b) 3D isosurface of the cold drifting species.

This theory can also be extended to the relativistic high anisotropy limit where kinetic effects (slopes of distribution functions) do not play a role which is more relevant to fast ignition. We have applied this theory to the distribution functions found in the global simulations of fast ignition and found reasonable agreement.

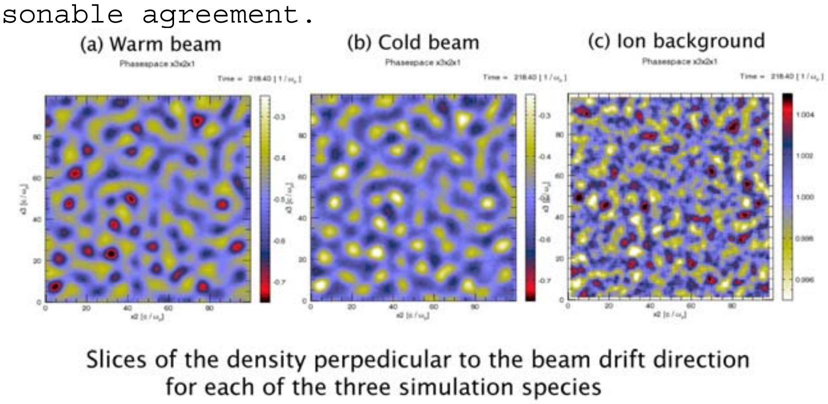

Figure 7: 2D slices of the three simulation species. The slice is taken perpendicular to the direction of the drift.

Publications and presentations:

1. Tzoufras, M., Ren, C., Tsung, F.S., Tonge, J.W., Mori, W.B., Fiore, M., Fonseca, R.A., Silva, L.O., "Space-charge effects in the current filamentation or Weibel Instability", Physical Review Letters, 96, 155003 (2006).
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Winjum, B. J., F. S. Tsung, W. B. Mori, "PIC simulations of laser-plasma interactions at intensities relevant to NIF," NP1.7, 2004 Annual American Physical Society – Division of Plasma Physics Meeting

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J. Fahlen, C. Ren, F.S. Tsung, M. Tzoufras, W.B. Mori, M. Marti, R.A. Fonseca, J.R. Davies, L.O. Silva, "Ion Acceleration Via Ultra Intense Laser Interactions with Over and Underdense Plasmas", Conference Poster presented at APS DPP Meeting 2004.

J. Fahlen, W.B. Mori, J. Tonge, F.S. Tsung, B. Winjum, A.B. Langdon, D.E. Hinkel, "Cavity Formation and Collapse in Stimulated Brillouin Scattering", Conference Presentation at APS DPP Meeting 2005

J. Fahlen, C. Ren, F.S. Tsung, M. Tzoufras, W.B. Mori, M. Marti, R.A. Fonseca, J.R. Davies, L.O. Silva, "Ion Acceleration Via Ultra Intense Laser Interactions with Over and Underdense Plasmas", Conference Poster presented at Anomalous Absorption Conference 2004.

J. Fahlen and W. B. Mori, "High-Mach Number Relativistic Ion Acoustic Shocks", Conference Poster presented at Anomalous Absorption Conference 2005.

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J. Fahlen, C. Ren, F.S. Tsung, M. Tzoufras, W.B. Mori, M. Marti, R.A. Fonseca, J.R. Davies, L.O. Silva, "Ion Acceleration Via Ultra Intense Laser Interactions with Over and Underdense Plasmas", Conference Poster presented at Stewardship Science Academic Alliance Symposium 2004.

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M. Tzoufras, C. Ren, F. S. Tsung, W. B. Mori, S. Amorini R. A. Fonseca, L. O. Silva, J. C. Adam, and A. Heron, *"The role of space charge on Weibel instabiliy"* APS DPP, Savannah, Georgia, November 15-19, 2004.

M. Tzoufras, C. Ren, F. S. Tsung, W. B. Mori, S. Amorini R. A. Fonseca, L. O. Silva, J. C. Adam, and A. Heron, *"The Weibel instabiliy in fast ignition regimes"*, Anomalous Absorption Conference, Gleneden Beach, Oregon, May 2-7, 2004.

M. Tzoufras, C. Ren, F. S. Tsung, W. B. Mori, S. Amorini R. A. Fonseca, L. O. Silva, J. C. Adam, and A. Heron, *"Energy transfer by self-consistently laser generated electrons in fast ignitor regimes"* Stewardship Science Academic Alliances (SSAA) Program Symposium, Albuquerque, New Mexico, March 29-31, 2004.

M. Tzoufras, F. S. Tsung, J. W. Tonge, W. B. Mori, C. Ren, M. Fiore, R. A. Fonseca, L. O. Silva, *"Emergence of space charge effects in the linear stage of the Weibel-like current* *filamentary instability"* Stewardship Science Academic Alliances (SSAA) Program Symposium, March 29-31 (2004), Las Vegas, Nevada, August 23-24, 2005.

Information for a project involving computer modeling:

We use the particle-in-cell method. . In fully explicit PIC codes the full set of Maxwell's equations are solved on a grid using currents and charge densities calculated by weighting discrete particles onto the grid. Each particle is pushed to a new position and momentum via self-consistently calculated fields. Therefore, to the extent that quantum mechanical effects can be neglected, these codes make no physics approximations and are ideally suited for studying complex systems with many degrees of freedom.

We has used our codes to study a variety of phenomenon including plasma based accelerators. We have compared the output from our codes against experiment observables. When these observables are reproducible in the experiments and the length and space scales have permitted full scale modeling we have found excellent agreement.

PIC codes have been around since the 1960s and numerous text books have been written on the method.